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Real Prognostics - Challenges, Issues, and Lessons Learned: Chasing the Big "P"

NASA ISHEM Conf. Napa Valley, CA.

7 - 10 Oct 2005

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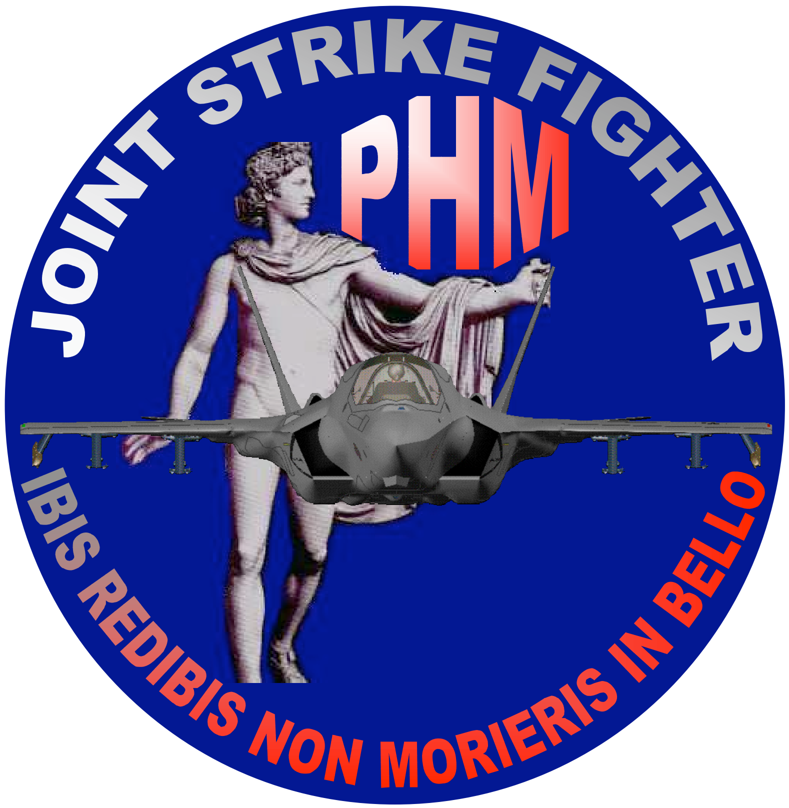
Joint Strike Fighter Program Office

VISION

BE THE MODEL ACQUISITION PROGRAM FOR JOINT SERVICE AND INTERNATIONAL COOPERATION

DEVELOP AND PRODUCE A FAMILY OF AFFORDABLE MULTI-MISSION FIGHTER AIRCRAFT USING MATURED/ DEMONSTRATED 21ST CENTURY TECHNOLOGY AND SUSTAIN IT WORLDWIDE

The PHM Logo – Part 2



REAL PROGNOSTICS – CHALLENGES, ISSUES, AND LESSONS LEARNED CHASING THE BIG "P"

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PROGNOSTICS & HEALTH MANAGEMENT

What is it?

- **Enhanced Diagnostics** –the process of determining the state of a component to perform its function(s), high degree of fault detection & fault isolation capability with very low false alarm rate
- **Prognostics** – actual material condition assessment which includes predicting & determining the useful life & performance life remaining of components by modeling fault progression
- **Health Management** – is the capability to make intelligent, informed, appropriate decisions about maintenance & logistics actions based on diagnostics/prognostics information, available resources & operational demand.

PHM Constituent Functions and Processes

- Fault Detection
- Fault Isolation
- Advanced Diagnostics
- **Predictive Prognostics**
- Useful Life Remaining Predictions
- Component Life Tracking
- Performance Degradation Trending
- **False Alarm Mitigation**
- Warranty Guarantee Tracking - Enabling New Business Practices
- Selective Fault Reporting
  - **Only tells pilot what NEEDS to be known immediately**
  - **Informs Maintenance of the rest**
- Aids in Decision Making & Resource Management
- Fault Accommodation
- Information Fusion and Reasoners
- Information Management
  - **Right info to right people at right time**

DETECTION, ISOLATION & PROGNOSIS

Detection

Through sensors, Models etc

Isolation

Information fusion from sensors, Models etc.

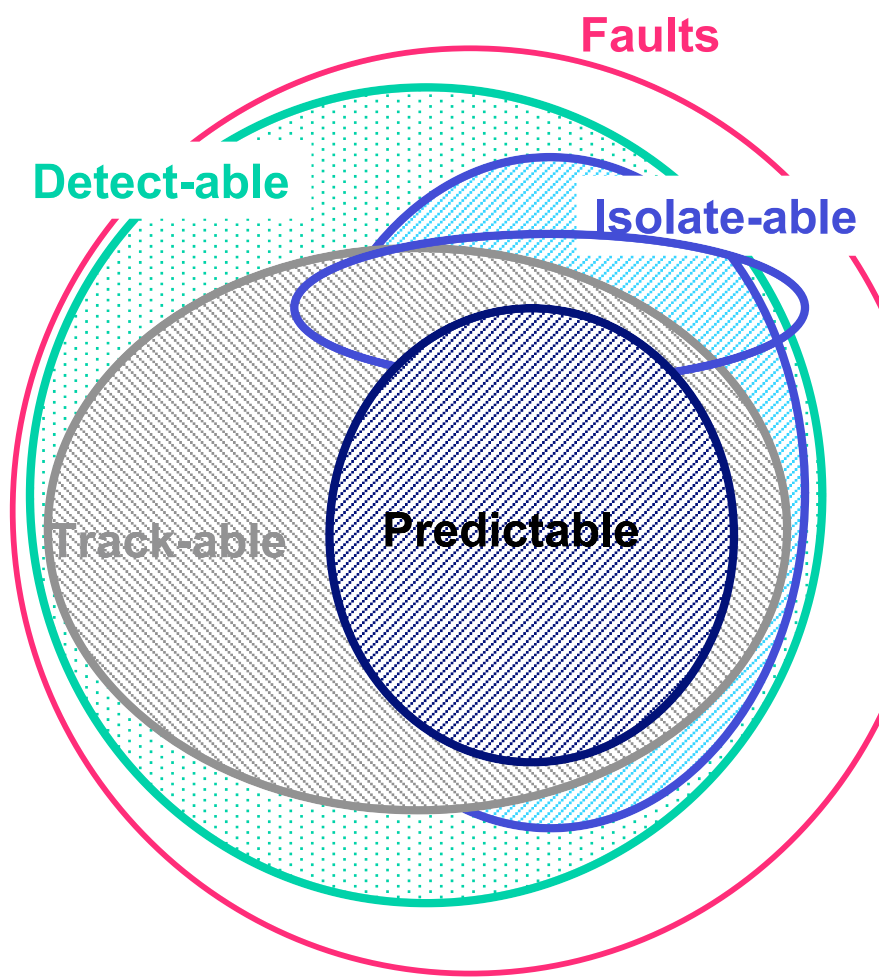
Tracking/Trending

Processed PHM data

(Off board PHM)

Prediction/Prognosis

Based on tracking/trending, & lifing models

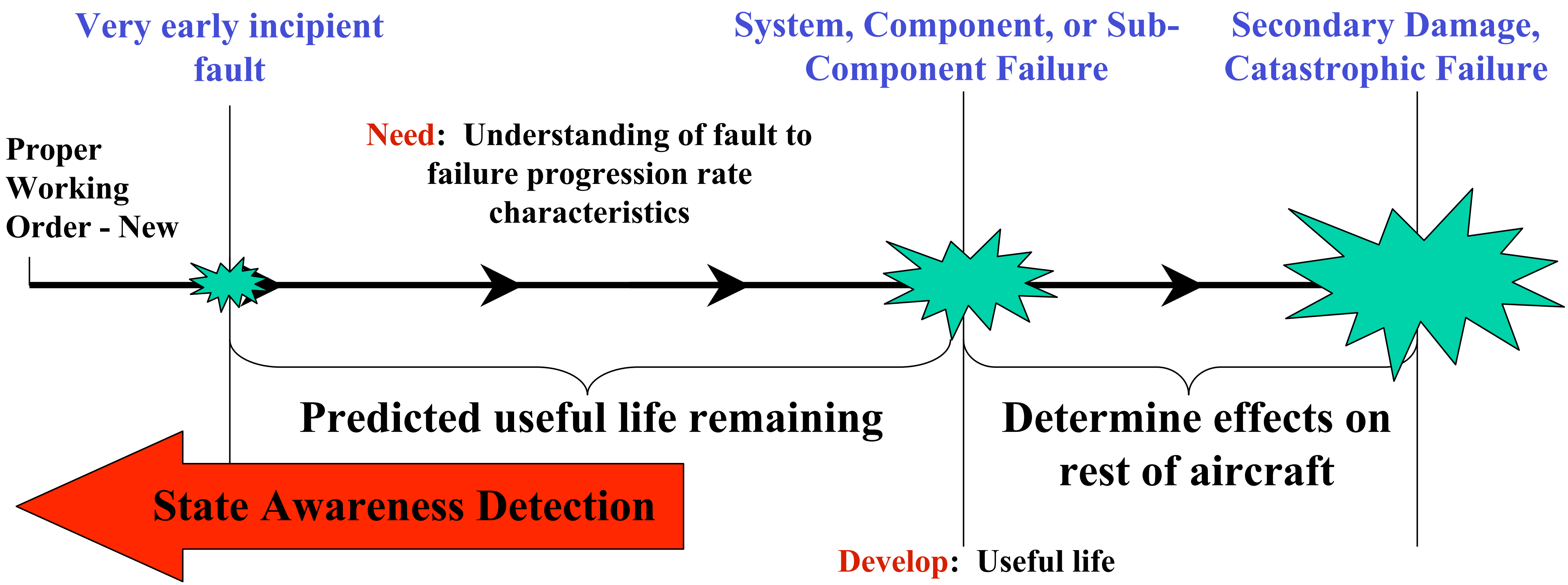


Failure Progression Timeline for a complex system

Prognostics

Need: To Manage Interaction between Diagnostics & Prognostics

Diagnostics



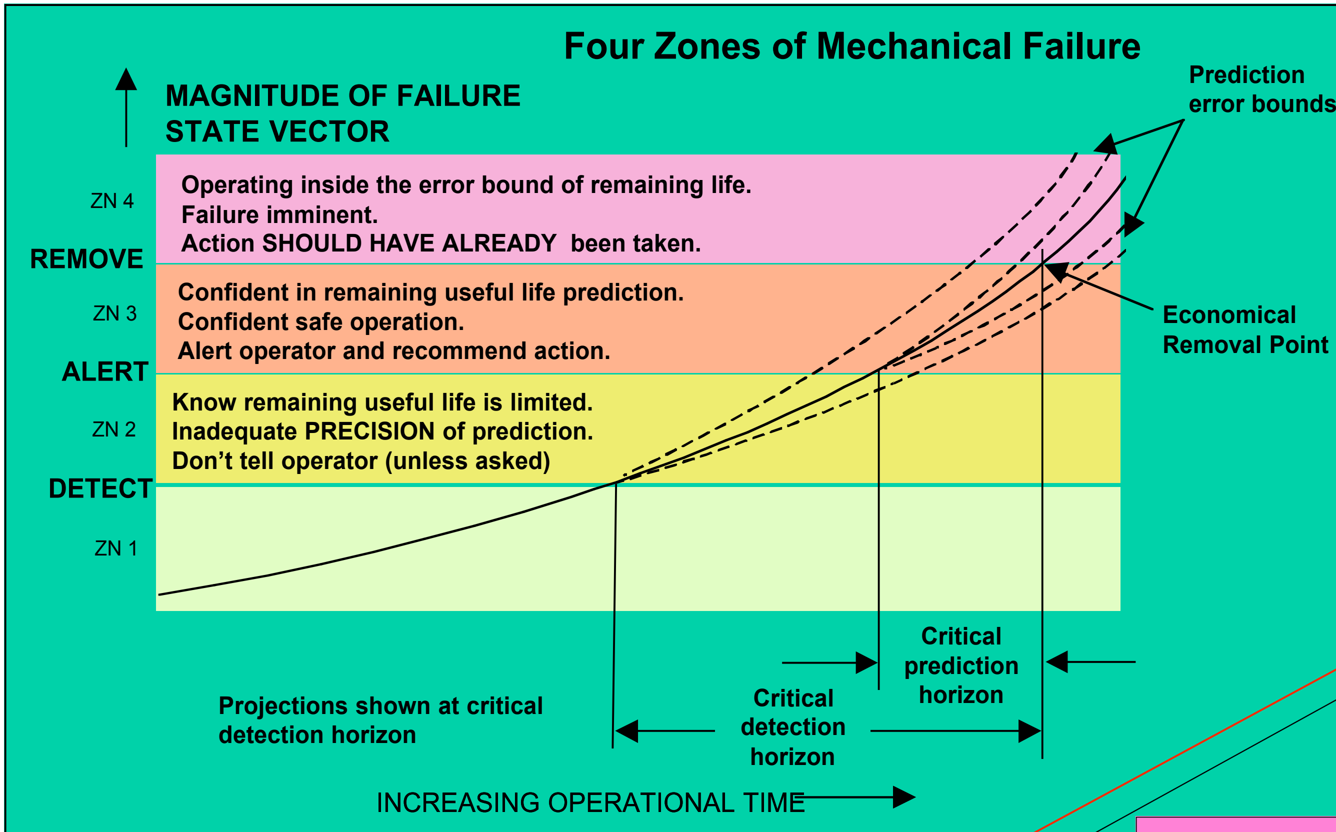
Desire: Advanced Sensors & Detection Techniques to "see" incipient fault

Develop: Useful life remaining prediction models – physics & statistical based

Need: Better models to determine failure effects across subsystems

The Goal is To Detect "State Changes" as Far to the Left As Possible

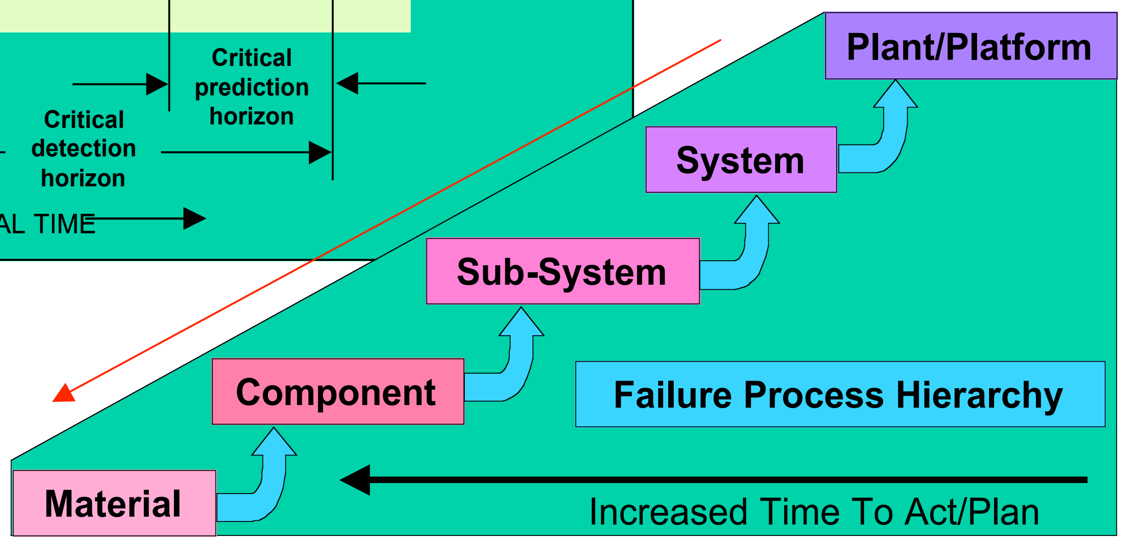
Typical Mechanical Failure Progression Questions



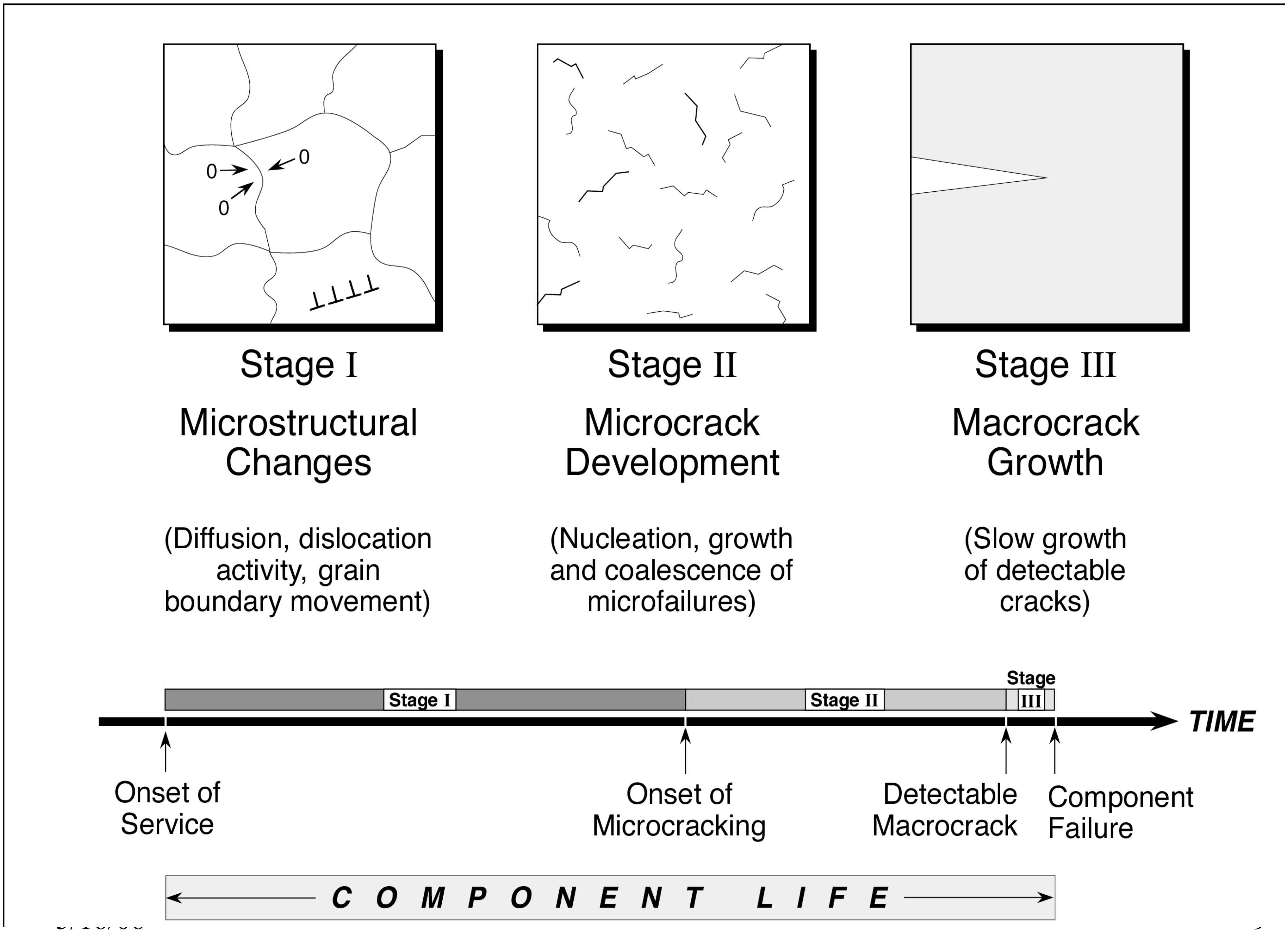
UNDERSTANDING THAT FAILURE IS A PROCESS NOT AN EVENT EMPOWERS A DETECTION PHILOSOPHY WHICH CAN BE EXPLOITED TO MANAGE THE EVENT THAT IS DEVELOPING NOT JUST REACT TO IT.

THE HIGER UP IN THE FAILURE PROCESS HIERARCHY THAT A FAULT IS DETECTED THE LESS MANAGEABILITY REMAINS AND THE LESS TIME EXISTS BEFORE FUNCTIONALITY IS COMPROMISED BEYOND THE USABLE STATE.

Key to Success is Understanding the Fault Progression Process for Critical Failure Modes. Understanding is best developed by testing.



DAMAGE EVOLUTION



Seeded Fault Crack Growth Successfully Detected Using Traditional Vibration Sensor and Advanced Frequency Analysis Techniques

H-60 IGB Pinion Gear Surface Inspection

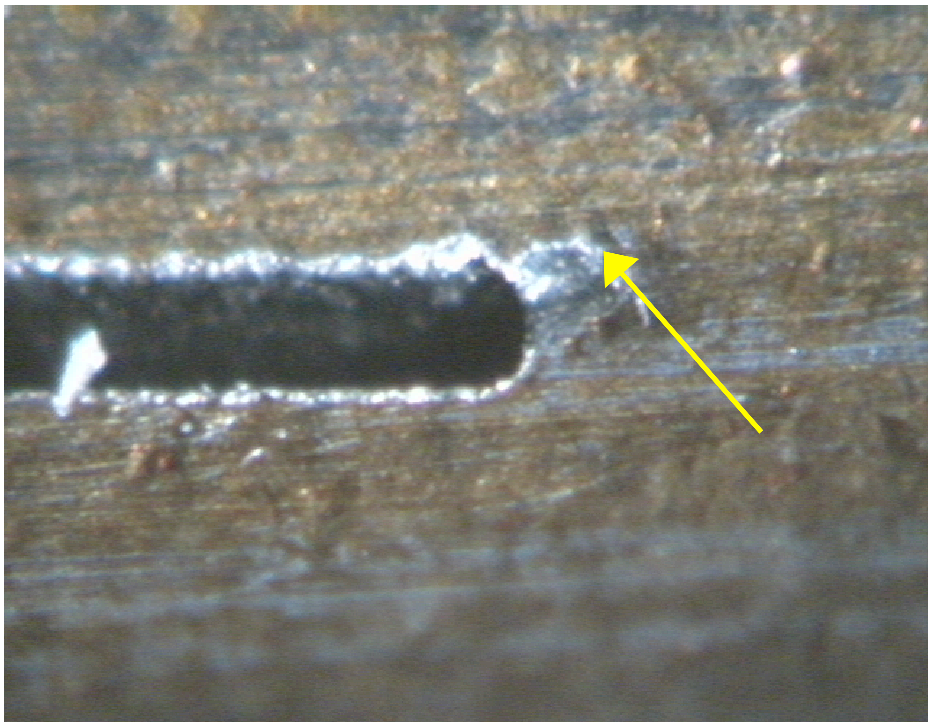


Image of heel notch inner end after Run 15, showing small chip liberated (arrow). No noticeable change until run 18.

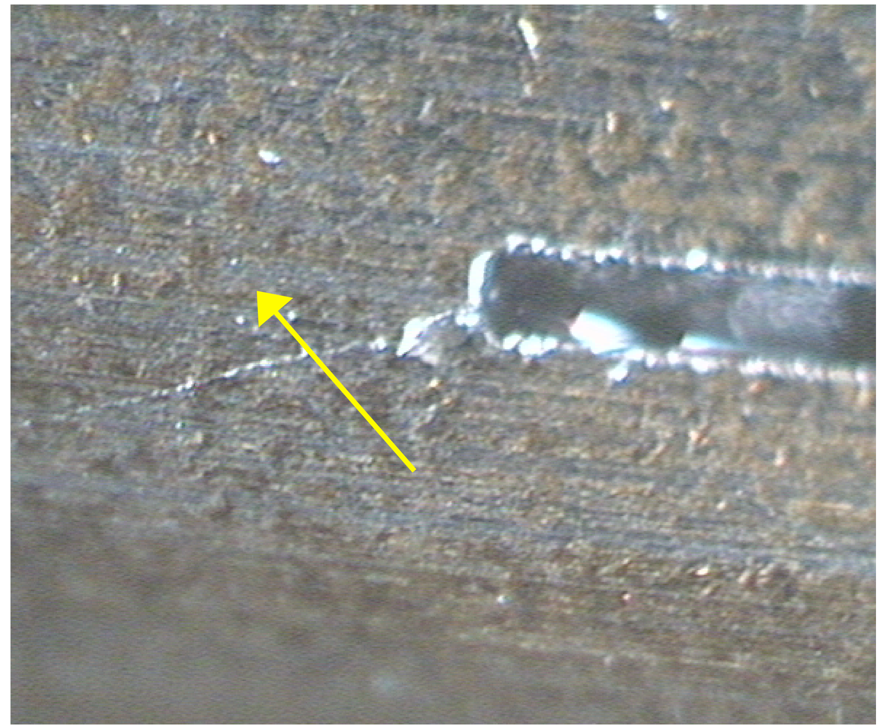
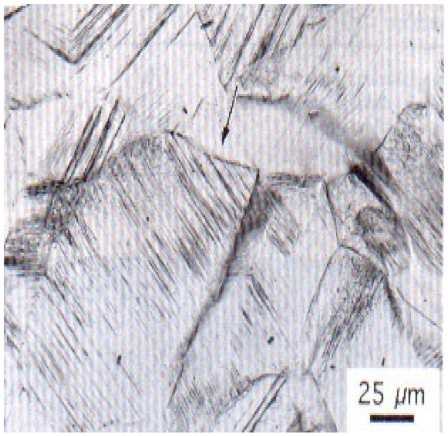


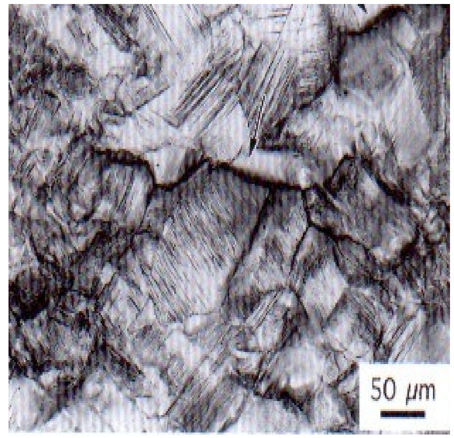
Image of heel notch outer end after Run 18, showing obviously visible crack (arrow).

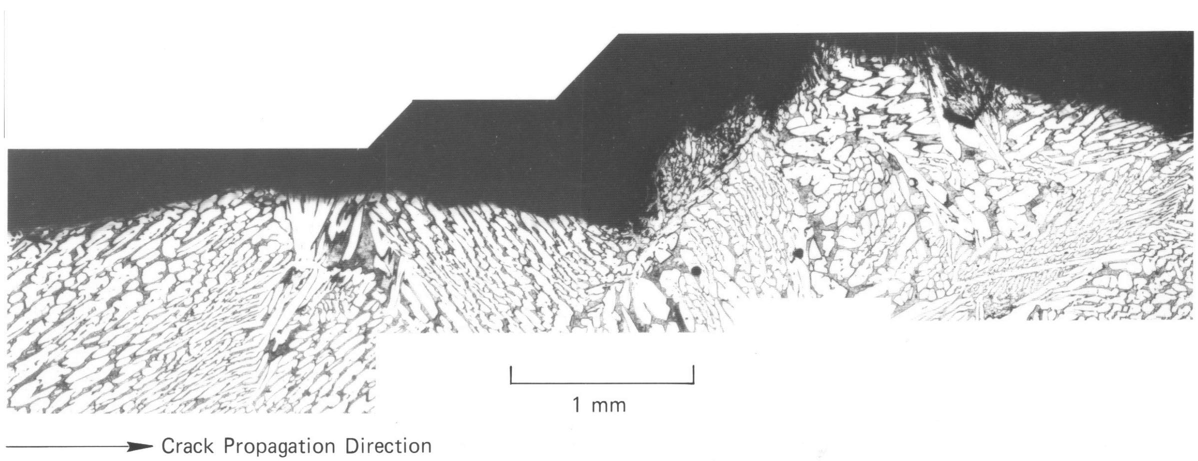
EVOLUTION OF FATIGUE DAMAGE IN NICKEL

After 1200 cycles



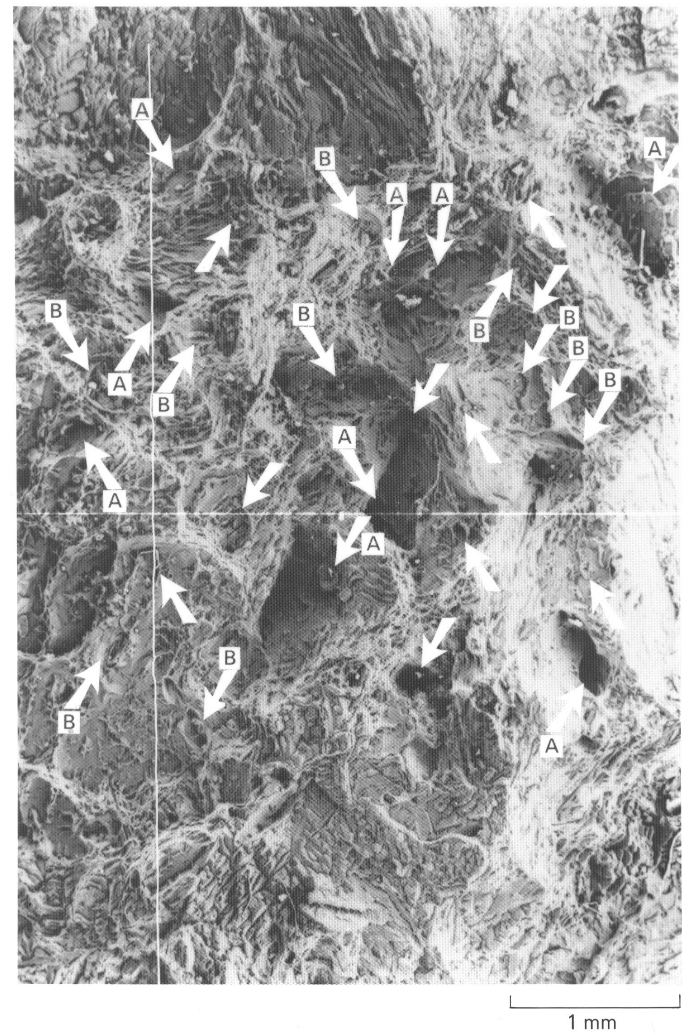
After 4000 cycles





Microstructure damage beneath fracture surface

Damage Nucleation Sites in the Microstructure

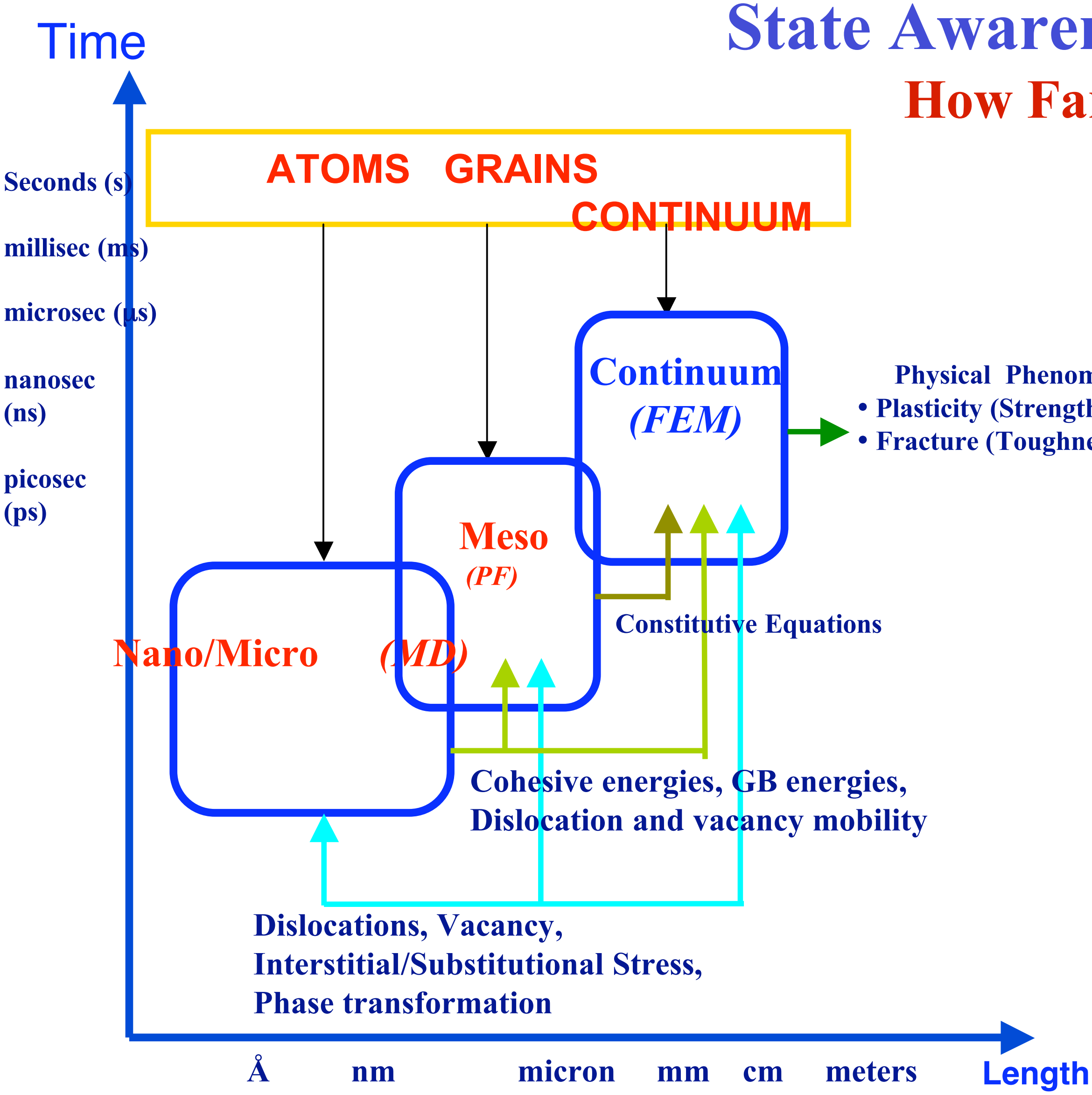


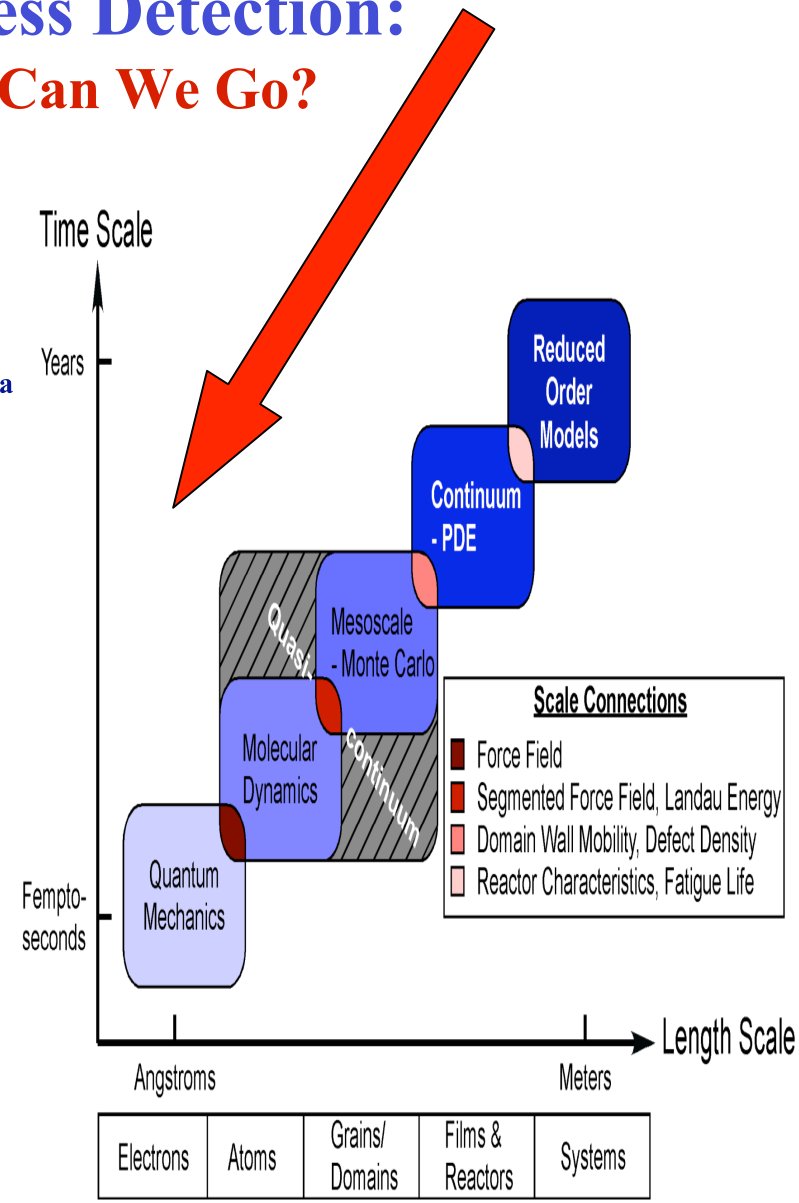
State Awareness Detection – How Far Can We Go ?

Bridging the Physical Scales

State Awareness Detection:

How Far Can We Go?

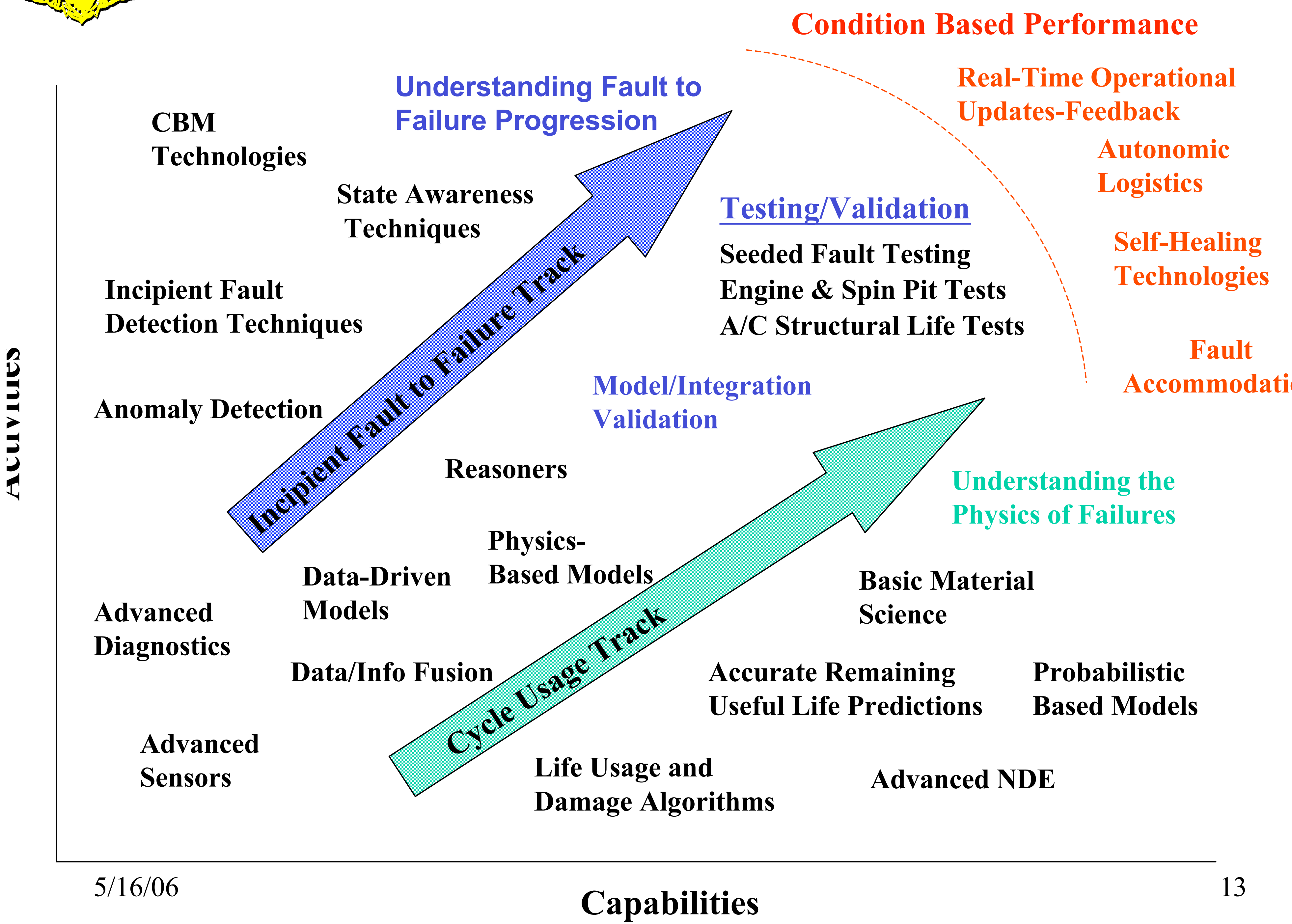




NAVAL AVIATION SYSTEM TEAM

Notional

Roadmap to Predictive Prognostics



Prognostics: What We Are Missing

- **Better Understanding of Physics of Failure**
- **Condition Based Performance Predictions**
- **Better State Awareness Techniques**
- **Better Understanding of Incipient Crack Growth**
- **Better Understanding of Fault/Failure Progression Rates**
- **Better Understanding of Material Properties Under Different Loading Conditions**
- **Better Data Fusion Methods**
- **Cost Benefit Models to Determine Practicality of Prognostics**
  - **Risk vs. Reward**
- **Better Knowledge of Effects of Failures Across the Air Vehicle**
- **Study to Determine What Components to Perform Prognostics On**

Notional strategy to demo predictive prognostics on helo drivetrain

- Identify and Target Components and Sub-elements suitable for Prognostics
  - Those with understandable fault to failure progression characteristics
  - Eliminate those impossible or too hard to consider
- Develop and/or Obtain advanced models
  - Fault to failure progression characteristics
  - Useful life remaining
- Perform experimental seeded fault tests
  - As many as affordable
  - Try to understand the physics of the failure
- Verify and validate models
  - Using seeded fault and blind test data
- Modify useful life remaining prediction model to account for real world considerations
  - Mission Profiles

Prognostics Maturation Strategy

Use E&MD Data to V&V Models

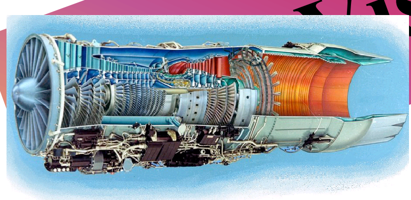
Use Condition Based Performance Predictions

Modify Algorithms to Account for Real World Considerations

ID Components and Sub Elements Suitable for Prognostics

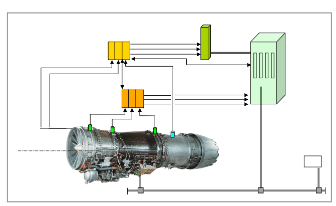
ID Technologies to Use

Eliminate Those that Are not Technically or Economically Feasible

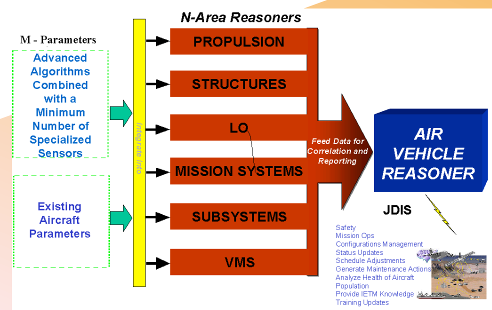


System Investigation

Test Configuration



Tech Maturation



Tech Integration

Intelligent Air Vehicle

PHM

Develop State Awareness Techniques

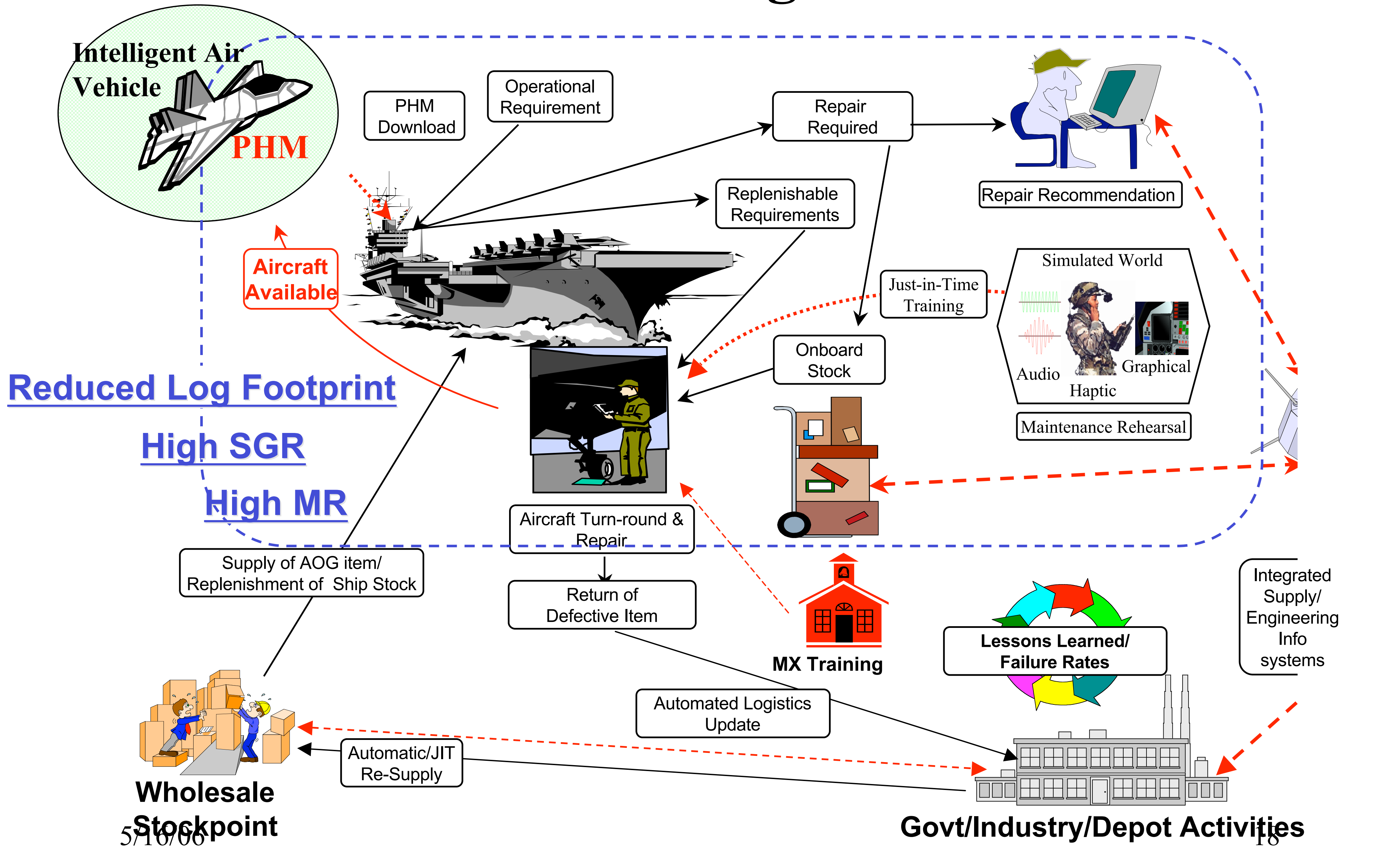
Perform Seeded Fault Tests

Understand "Physics of Failure"

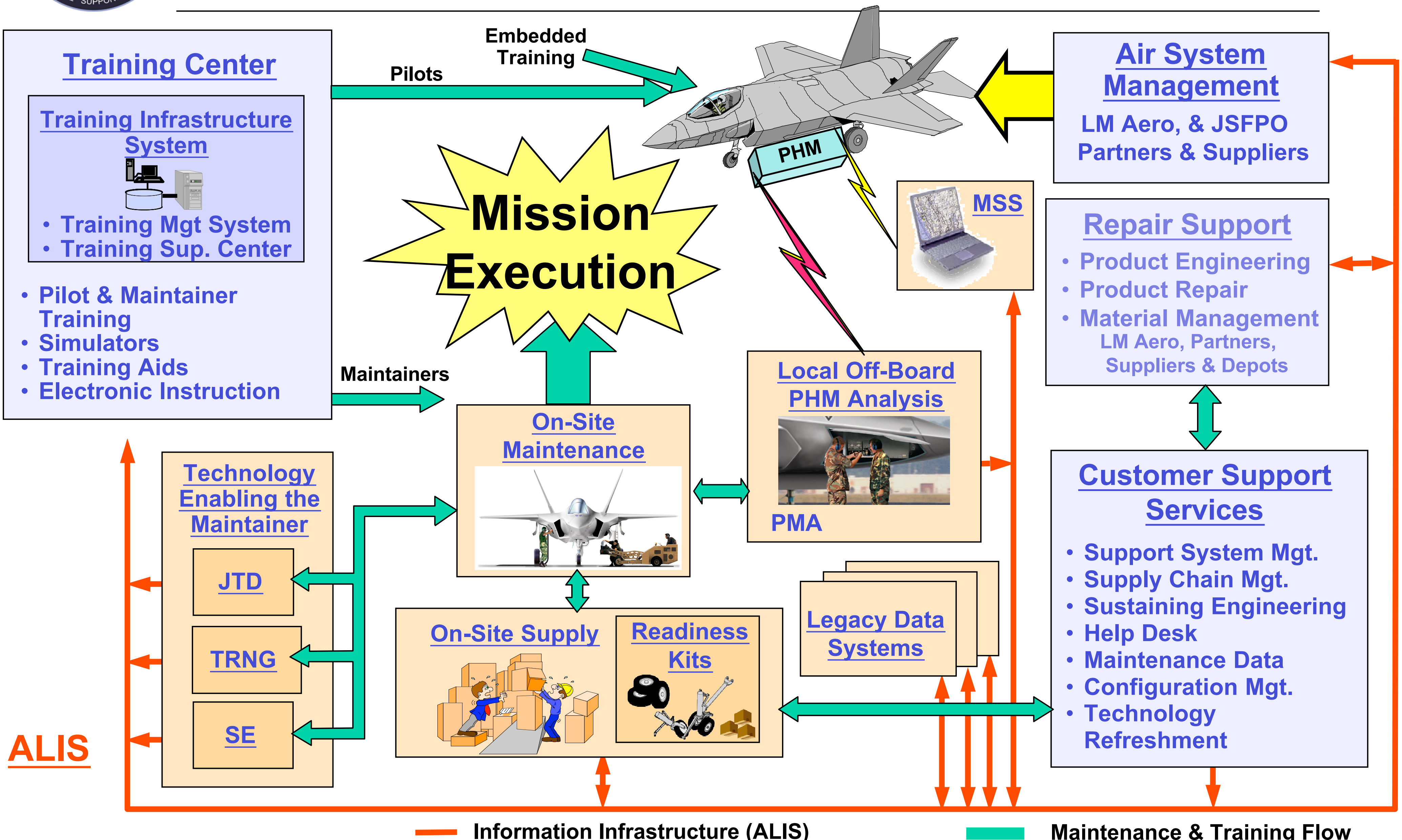
Combine All Aspects into Air Vehicle

The PHM Logo – Part 3

PHM Is the Air Vehicle Enabler of the Autonomic Logistics Structure

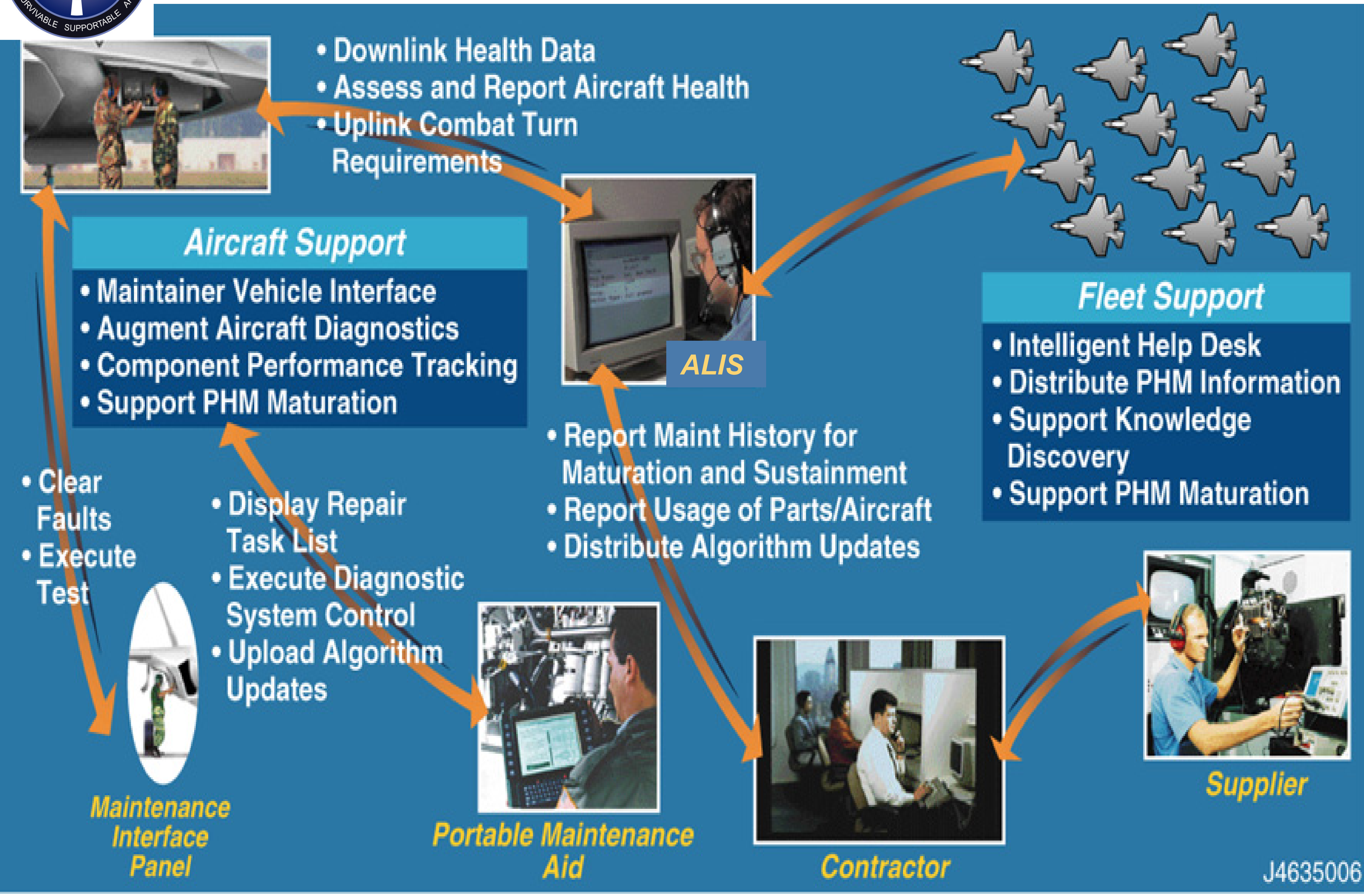


AUTONOMIC LOGISTICS SYSTEM



Autonomic Logistics Provides Faster Repair with Fewer People Resulting in Increased Air Vehicle Availability at a Lower Cost

Off-Board PHM Overview



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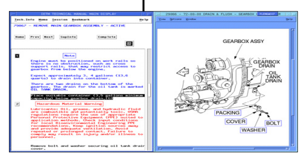
Logistic Operations

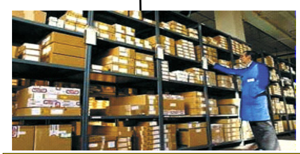
Future aircraft Logistic Support vision is an organization responsible for Global Technical Support to “warfighters” (peace/crisis), managed by a joint team (Govt./Contractor). “Legacy” Govt. activities will be reallocated under contractor’s management (Government visibility).

Logistic Support

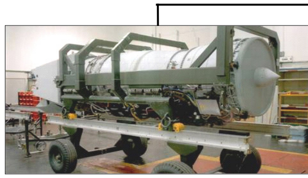
Fleet Management



Sustaining Engineering

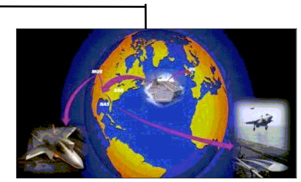


Supply Chain Mgt



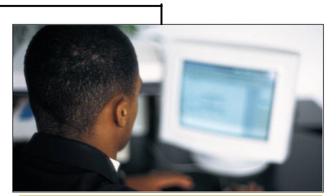
Support Equipment Mgt

Training Operation



Information System Support

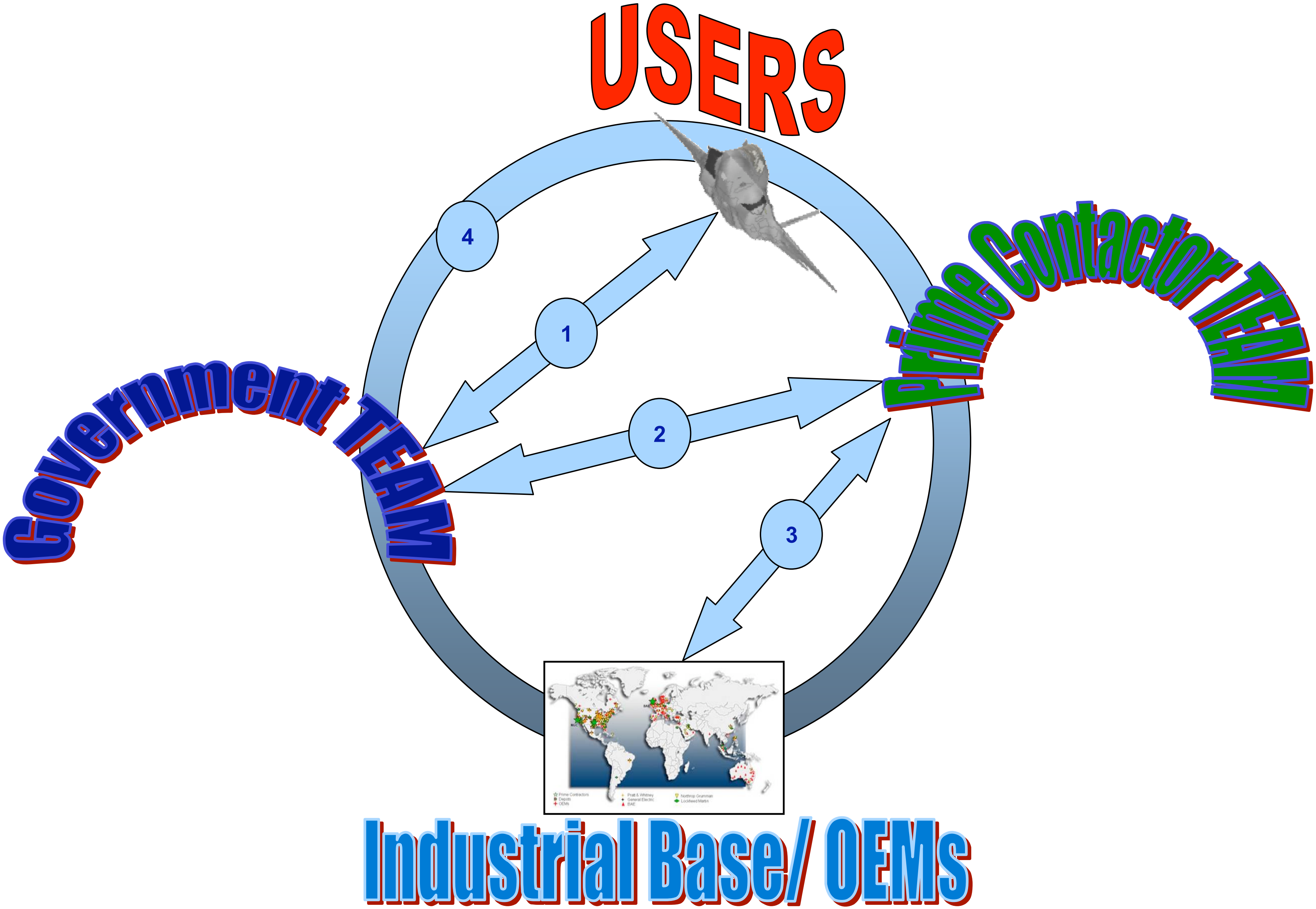
Logistics Field Operation



Business Operations

Logistic Support Development

Global Sustainment Strategy



A performance-based approach

Legacy renegotiable price based contracting will be abandoned over time shifting gradually to new long-term Performance-based contract: an approach for buying set levels of performances.
Example: LRIP cost-type award fee (as the design matures, defined enablers are achieved, sufficient reliability and cost data are obtained) --> fixed-price (established criteria and performance metrics) --> Performance-based.

- Reduce Total Ownership Costs.
- Increase Users Confidence and Satisfaction.
- Facilitate Contractor-Government Integration & Communication.
- Reduce demand for logistics.
- Incentivize Reliability Enhancements.
- Decrease the Resource Requirements for Support.
- Encourage manufacturing obsolescence planning.
- Centralize Management.
- Create a Real Time Problem Response (24/7).
- Optimize the Technology Insertion.
- Utilize a consistent Life-Cycle Cost Analysis.
- Optimize infrastructure harmonization and asset utilization.

Prognostics

Fundamental factors that influence the decision to shift to this new business approach.

With this concept, Original Equipment Manufacture (OEM) and Suppliers make capital investments in new technology, knowing that their involvement (and related profits) will extend into <u>Production and Post-production</u> phases.

Challenges to Optimum Business Solution

To develop an optimum Performance-based, it is needed to evaluate challenges:

- **Consensus on Performance-based business solution**
- **Long-term contract commitment from both the Gov. and Contractor**
- **Authorization/regulatory relief for Business Case Options in conflict with current rules and regulations**
- **Funding complexities**
- **Availability of appropriate legacy cost data**
- **Acceptance of new Logistic solution at all levels**
- **Mutually agreed-to performance metrics**
- **Ownership/management/sharing of spares and support assets**
- **Services/public sector accountability**
- **Title 10 compliance**
- **Propulsion integration approach**
- **Supplier willingness to commit to the recommended Business Approach**
- **Government willingness to accept reductions with new logistic infrastructure**
- **Change management**

Prognostic in business model

“P” influences various attributes (i.e. support equipment, maintenance, supply chain, spares ownership/management, propulsion support).

Real challenge: develop valid and measurable metrics for quantifying the impact of the various “P” technologies on the individual model attributes and to include these in the business model

Business Model

In order to ensure that system design is properly balanced between 5 management categories, establishment of business model is the framework for assessing correlation of business elements and attributes, that are functions and tasks required to perform the 9 logistics operations and that will allow the assessment of best value solution

	Category				
	I	II	III	IV	V
Management – Government	Total	Program Management	Approval	Oversight On Limited Tasks	Insight/Oversight by Exception
Management – Prime	None	As Directed	Program Management	Shared Approval	Total Approval
Performance	Government	Government with Prime Support	Prime with Gov't Support	Prime Only or Shared	Prime Only
Business Model Elements					
Sustainment Integration	Government				Total Contractor
Joint Fleet Management	Government				Total Contractor
Sustaining Engineering	Government				Total Contractor
AL Field Operations	Government				Total Contractor
AL Information Systems	Government				Total Contractor
Supply Chain Management	Government				Total Contractor
Support Equipment	Government				Total Contractor
Depot Maintenance	Government				Total Contractor
Training System	Government				Total Contractor
Facilities, Manpower Other Gov't	Government				Total Contractor

Uncertainty - Design Issue

- One of the major challenges to the designers of modern PHM systems is the need to develop diagnostic and prognostic methods that are truly capable of handling real-world uncertainties – as the real world is not deterministic.
- Such real world uncertainties cause havoc with deterministic approaches leading to high false alarm rates, inaccurate predictions, incorrect decisions and an overall PHM system that is not very robust.
- Some of the issues uncertainty presents to the designer are discussed.

Uncertainty – Current Condition

- The first step in predicting remaining life or time to failure is to know where you are at any time along the continuum of condition from normal to degraded to fail – i.e. the current condition.
- Uncertainty associated with the estimate of current condition flows through to and compounds the inaccuracies of the predictive process itself and so good prognostics starts with good diagnostic design.
- For affordability reasons, most PHM designers can not rely on a PHM specific sensor based solution but rather have to rely on sensors placed for other functional purposes, such as control. This is especially so when attempting to maximize diagnostic coverage.
- Consequently, direct measurement of condition is more the exception than the rule in operational PHM systems. Rather condition has to be inferred from an appropriate choice of sensors and parameters – or features.

Uncertainty – Good features

- Good features will exhibit wide separation - distance- between the normal and failed values with low uncertainty and bad features will exhibit small separation with high uncertainty.
- So for bad features there is a high likelihood that the distribution of feature values that represent a given healthy state - normal condition - will overlap the distribution of feature values that represent a failed state.
- Such an overlap means at the same feature value one gets both a probability of a false positive and a false negative. The relative probabilities are determined by the shape of the feature distributions and the location of the threshold value.
- The implication is that the diagnostic performance of a badly chosen feature is not necessarily improved by tweaking the thresholds but rather by paying closer attention to uncertainty in the design process.
- Furthermore, any such feature that does not provide good discrimination between the normal and failed condition is not likely to be a good feature for prognosis. The designer needs to go back and choose a better feature.

Uncertainty- Prediction

- Given the future is not fully known or knowable the prediction of remaining time (ie time to failure or life remaining) needs to be treated as a probabilistic process where the predicted remaining time is represented by a probability density function.
- Importantly, the accuracy and uncertainty (precision and confidence) of the predicted remaining time are adversely impacted by the stochastic processes yet to happen.
- Whilst it is useful to try and quantify such future events and behavior and determine the most likely scenarios, one cannot know exactly what will happen and so the resultant inaccuracy and uncertainty of the predicted remaining time can only be minimized at best but not completely eliminated.
- The use and interpretation of probability density functions throws up the following paradox: the more precise the prediction of remaining time, the less probable this prediction will be correct.
- This behavior means the designer must pay close attention to how far ahead failure, life or condition needs to be predicted

Uncertainty- Lead Time Interval

- What is good enough for a prognostic estimate in terms of accuracy and precision is more a function of how far ahead one needs to predict – the lead time interval. This is in turn a function of the users needs and the overall logistic system the predictions fit into.
- Simple analysis or judgment calls can provide appropriate lead times for various needs such as, turn around – sortie generation rate, spares ordering - supply chain management, and scheduling the removal of life limited components - fleet life management.
- More complex is determining whether the lead times so chosen provide the necessary system wide impact – optimal system of system behavior with overall lower cost of ownership.
- Currently, the designer is short of such tools and like in most PHM cost-benefit studies the designer would benefit from improved models of how PHM interacts with and impacts the total logistic system.
- The designer having determined the appropriate lead times for a given, failure mode / LRC can then proceed to develop and use different prognostic methods as the different lead times can tolerate different accuracy and precision.

Uncertainty – Impact on Design Approach

- No one method will provide a useful, robust and comprehensive prognostic capability for a total aircraft logistic system of system.

- An integrated approach is needed combining information from the individual detection, diagnostic and prognostic functions at the appropriate component, Line Replaceable Unit, sub-system, system and system of system levels and from both on-board and off-board sources.

- The prognostic approach will also vary depending of how well the system behavior and failure mechanisms are understood and how well the aircraft sensors, and maintenance and logistic systems capture and use the required information.

- The approaches will necessarily involve a mixture of physics / model based, rule-based and data driven algorithms embedded in an artificial intelligence reasoning framework to enable the desired automatic decisions to made in the presence of uncertainty.

Lessons Learned

- **Prognostics Capabilities are mostly Hard to Develop, take Time to Mature, but are Doable in Many but Not all Cases**
  - Identify Cases that are Not Doable and don't Worry about them
  - Focus limited Resources on Doable and High Value Components
- **Need Good Diagnostics before Doing Prognostics**
  - Having Diagnostic it follows you will attempt to develop Prognostics
- **Simple System Performance Degradation can be very Useful**
  - Use on "low hanging fruit" where Trends can be easily Understood
  - Where Physics of Failure Models Not Available or Root Causes are Random
  - Without or before Accurate Useful Life Remaining Predictions
- **Significant Data, Experience, and Maturation Time is Req'd to Develop Prognostics and Accurate Life Remaining Predictions**
  - Plan for this with Resources, Maturation Strategy, Mgt Commitment

Lessons Learned

- **Prognostics with Accurate Useful Life Remaining Predictions**
  - Needs Multiple Types of Integrated Models
  - Physics of Failure Knowledge
  - Sensor based, Accumulated Usage, Fault Propagation, Statistical, etc.

- **Successful Develop of Global Prognostic Models Requires Multi-Discipline Team, Specialists, and Experts**
  - Material Science, State Awareness Sensor, Diagnostics Experts
  - Several Types of Modeling, Data Fusion, Probabilistic, Specific Component Design Specialists, etc.
  - Legacy Efforts often short on Material Science Expertise

- **Subsystem Expertise and Knowledge of Failure Critical**
  - It all Starts with the Subsystem Suppliers
  - Seeded Fault Tests Invaluable but Very Expensive – plan Wisely
  - Leverage off "Piggyback" Testing and Test Opportunities

- **Unlikely a Single Platform can Afford all the Resources Req'd**
  - Smart Strategy to Share Development Costs Across
  - Aggressively Use "Outside" S + T Efforts and Opportunities

- **Justify Benefits and Prepare for Funding Challenges**

Lessons Learned

- Performance Based Specs "are Not Ideal" for PHM
  - If you Know What you Works and you want, Specify it
  - If you Know What doesn't Work, write a Spec Req't so you don't get it
- The big Prime Contractors want to be System Integrators but don't Necessarily have the "niche" Technologies and Expertise to Provide Fully Capable, State-of-the-Art PHM Capabilities
  - If a technology or capability isn't Mature and COTS, they don't want it
  - Keeping Management Commitment among Design/Cost Pressures through the course of the Development Program is very Challenging
- Much of the New and Innovative PHM Technologies and Capabilities are Reside in the Small Business arena
- Look for Feeder Technologies for New PHM Capabilities in other Related and Non-Related Disciplines and Industries
  - e.g., much of the Advanced Vibration Diagnostics used in Gearbox Monitoring came out of the signal processing and data analysis techniques found in ASW

Lessons Learned

- PHM is a Multi-Disciplined, Multi-Functional, Multi-Technology, Multi-Faceted Endeavor
  - Understand this and Plan to Deal with it
- On-Board and Off-Board PHM Capabilities Need to be Designed and Developed at the Same Time, Together, and Integrated by the Same Prime Contractor
- On-Board and Off-Board PHM Algorithms Need to be the Responsibility of the On-Board, Air Vehicle, Subsystem Specific Engineering Design Teams
  - This includes Development, Validation, and Verification
- Mission System and Avionics Infrastructure Issues can Significantly Limit PHM System Development and Maturation
  - Dependence on their Hardware, Through put, Processing, Storage, Software, etc. to Implement our Capabilities
  - They are always a Problem and always let you down

Lessons Learned

- PHM as a Robust Data Acquisition System will Surprise you as it aids in Addressing TBD Problems that it wasn't Designed to Address
- More Data is Better. Learn to Handle it and Manage it.
  - Even with a Fully Automatic PHM, Pilot Recording is Useful
- PHM, R+M, System Integrity, and Safety Disciplines are Married at the Hip
- Autonomic Logistics or its equivalent is PHM's main Customer, but they Easily Fall Back on Legacy Supportability Approaches. Their Effectuation is Extremely Important but Difficult
- PHM Must be Part of the Overall System Design Process and its many Trade Studies

Summary and Conclusion

- **Benefits of Predictive Prognostics are Real, Great, and Obvious**
- **Real Predictive Prognostics is New, very Challenging, and Requires Significant Resources and Maturation Time**
- **Several Types and Degrees of Prognostic Capabilities**
  - Current Developing and Evolving
- **Prognostics is just one part of the PHM Capabilities Set**
- **Prognostic Capability is a Key Enabler to the Performance Based Logistics Concept**
- **Challenges, Issues, and Lessons Learned are Many and will Continue to grow**
- **Stay Tuned for follow on parts of this paper: "Chasing the Big P"**

Ending Thoughts ….